NASA TECHNICAL TRANSLATION NASA TT F-14,205

METEOROLOGICAL ROCKET COMPLEX M-100 USED FOR ATMOSPHERIC SOUNDING IN THE USSR

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ABSTRACT: The M-100 meteorological rocket, its instrumentation, and operating principles, are described. The procedure used to process measurement obtained, and the use to which put, are discussed.

The M-100 Rocket

The M-100 Soviet rocket complex for meteorological research consists of an /1* installation for launching the rocket, the equipment designed to measure and transmit information, and the ground equipment for receiving and processing the information.

The rocket is a two-stage, unguided, solid fuel rocket capable of lifting the instrumentation to an altitude of about 100 kilometers (see Figures 1a and 1b).

The rocket is launched from a launcher consisting of a carriage and spiral launching rails which, together with the offset fins, ensure rotation of the rocket about its longitudinal axis and give it stability in flight (Figure 2).

The rocket is placed in the installation with the rails in the horizontal position. The rails then are moved into the launch position on predetermined azimuth and elevation angles. These angles are determined from tables that include the effect of wind on rocket movement.

The protective panels that cover the instruments are jettisoned during the ascent, and this is followed by separation of the head of the rocket and simultaneous activation of the parachute. The separation device imparts additional velocity to the head upon separation. This reduces, in particular, the possibility of the rocket body damaging the parachute. Most of the measurements of atmospheric parameters begin when the rocket head separates. The head, descending on the parachute, begins to drift at an altitude of 65-60 km during /2 the descent stage of the trajectory. The parachute acts as a stabilizer down

* Numbers in the margin indicate pagination in the foreign text.

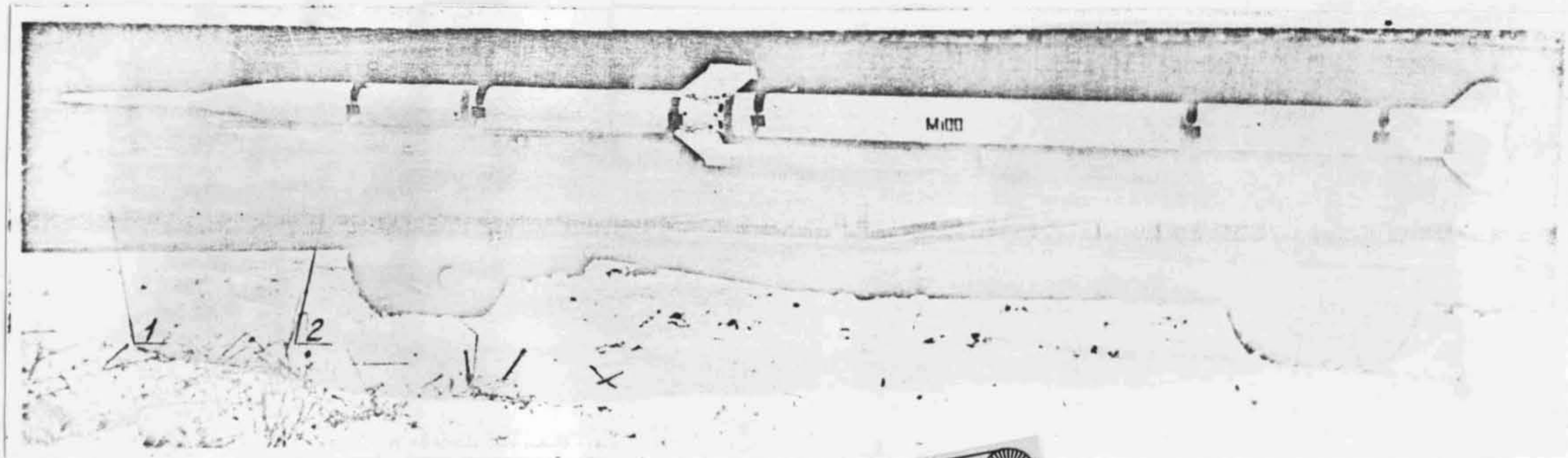

Figure 1a.

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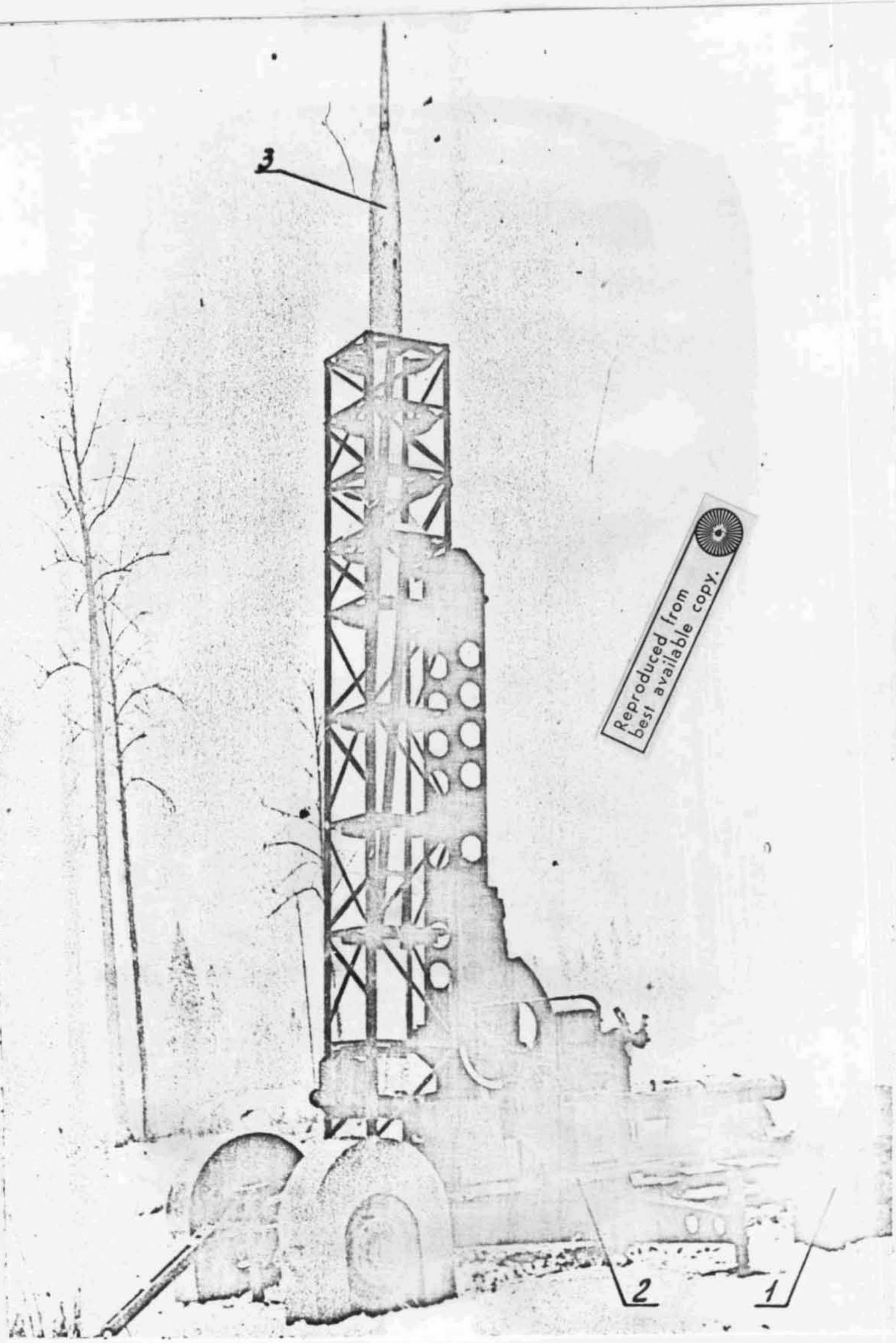


Figure 2.

to this level. The electrical commands to jettison the protective panels, and for separation of the rocket head, are given by the time command mechanism.

<u>Technical Data for Rocket</u>

1. Rocket launch weight (kg)	480.0
2. Caliber (m)	0.250
3. Rocket length, overall (m)	8.240
4. Weight of first stage engine (kg)	290.0
5. Weight of second stage engine (kg)	122.0
6. Weight of instrument compartment and recovery system (kg)	66.7
7. Powder charge	cylinder single-perforate grain, end-restricted
8. Weight of first stage engine powder charge (kg)	182.4
9. Weight of second stage engine powder charge (kg)	64.7
10. Fin span, first and second stages (m)	0.68
11. Temperature range for use of rocket (°C)	+40 to -40
12. Timers	mechanical, started by withdrawal of safety bars
13. Stage separation time (sec)	8.0
14. Stage separation system	shearing of special bolts by II stage engine thrust
15. Time to jettison spire protection panels (sec)	60.0
16. Panel jettison system	pressure of gases from an pyrotechnic device in the front part of the panels
17. Instrument compartment separation time (sec)	70.0
18. Head separation system - descent attached mechanically to the parachute under action of thrust of a special separation engine	
19. Altitude of head separation (m)	68000 to 74000

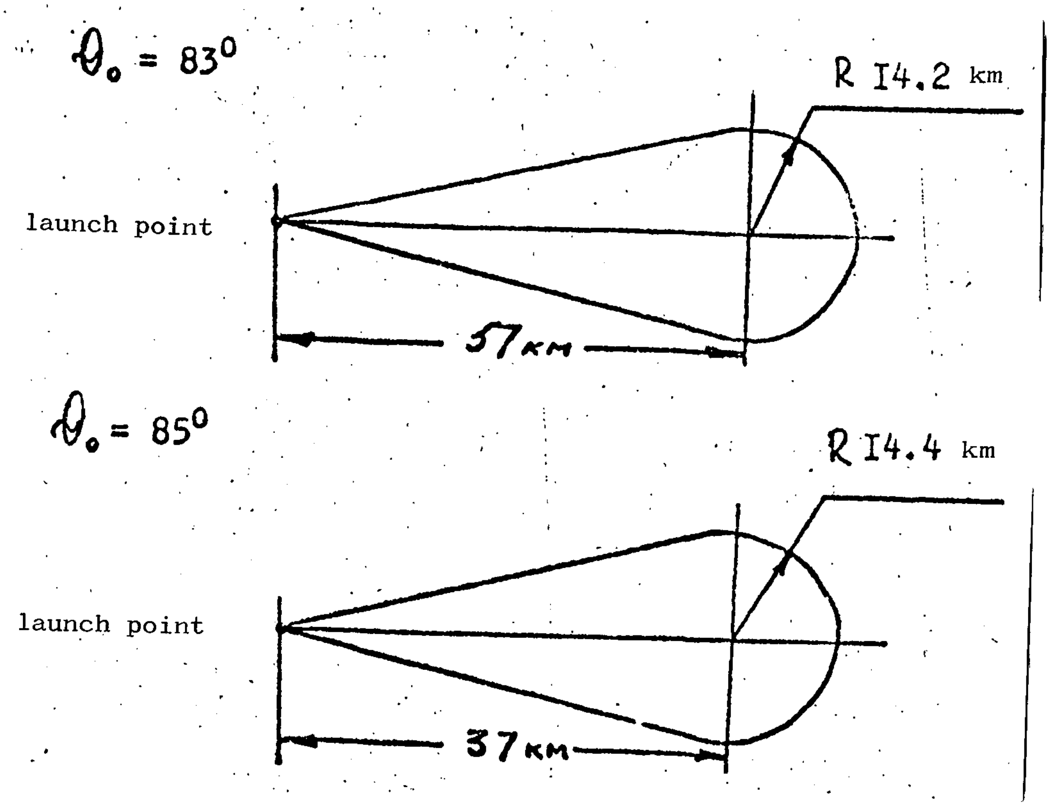
20.	Maximum altitude reached by instrument compartment for angle of elevation 85° (m)	95000
21.	Type parachute	hemispherical
22.	Area of canopy (m^2)	34
23.	Material	capron

Technical Data on Launcher U-100

1.	Weight (kg)	9200
2.	Height in housed position (m)	2.820
3.	Width in housed position (m)	2.350
4.	Length with boom (m)	8.600
5.	Maximum angles of vertical guidance (degrees)	-3 to +85
6.	Guidance angle in horizontal plane (degrees)	±720
7.	Number of spiral launching rails	4
8.	Drive for raising the cradle	manual and electromechanical
9.	Electric drive operates off 380 volts, 50 Hz, 3-phase AC	
10.	Width of rail (m)	1.820

A crew of 3 or 4 men can do the work associated with assembly, checking, /4
transporting, preparing the engines and launching the M-100 meteorological rocket.

Data on wind in the 0 to 3000 meter layer, used to calculate the correction made to the launcher sighting angle, should be known at least 20 minutes prior to launch. The rocket can be launched when the ballistic wind in the above layer is under 15 m/sec. The zone in which the spent second stage will fall has the shape shown in the sketch. At the same time, the points of fall of the first stage engines are inside this shape.



Rocket Equipment

The rocket head consists of a spire and the instrument container. /5

The spire carries two Pirani heat gauges, four resistance thermometers designed to measure the temperature of the atmosphere, and two resistance thermometers designed to measure the temperature of the heat gauge walls and the temperature of the strut to which the main resistance thermometers are secured.

The instrument container contains the diaphragm gauge, the transmitter for the radio telemetry system, the radar responder with its antenna-feeder system, the mechanical switch, the power source for supplying the instruments, and the command mechanism. All the instruments are mounted on an instrument rack installed in the envelope of the rocket head (Figure 3a, b, c). The protective panels protect the instruments in the spire from damage during passage through the dense layers of the atmosphere. The rocket head has an overall length (with spire) of 1950 mm, and a maximum diameter (at the base of the envelope) of 250 mm.

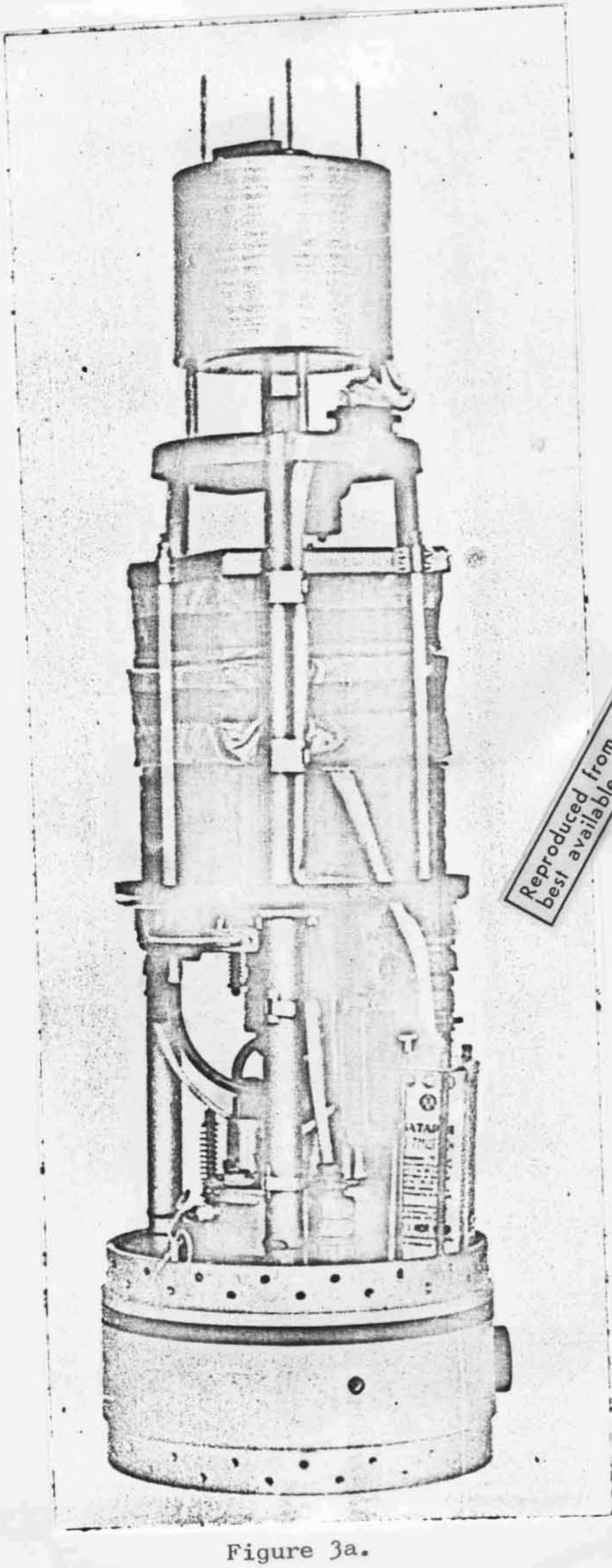


Figure 3a.

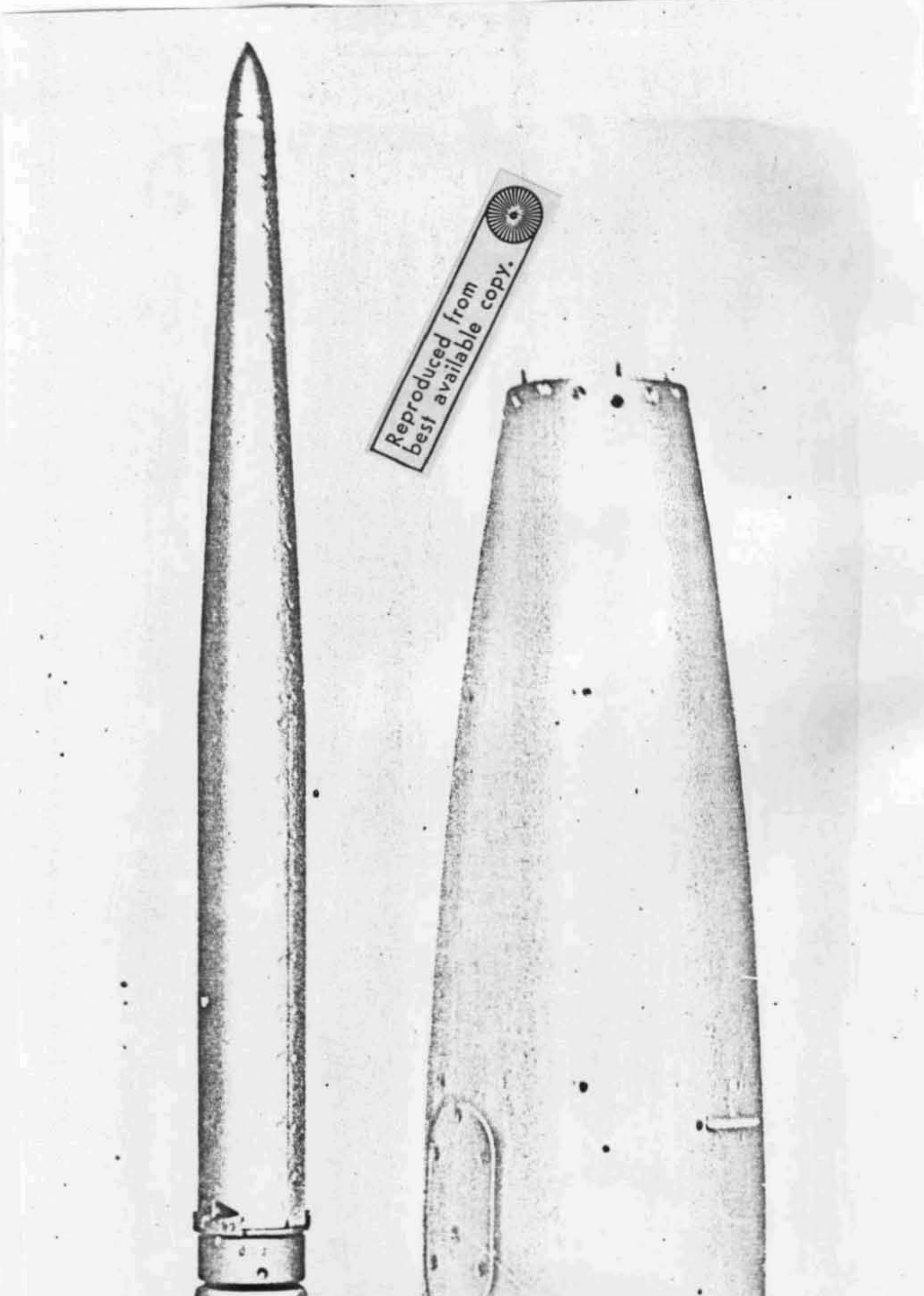


Figure 3b.

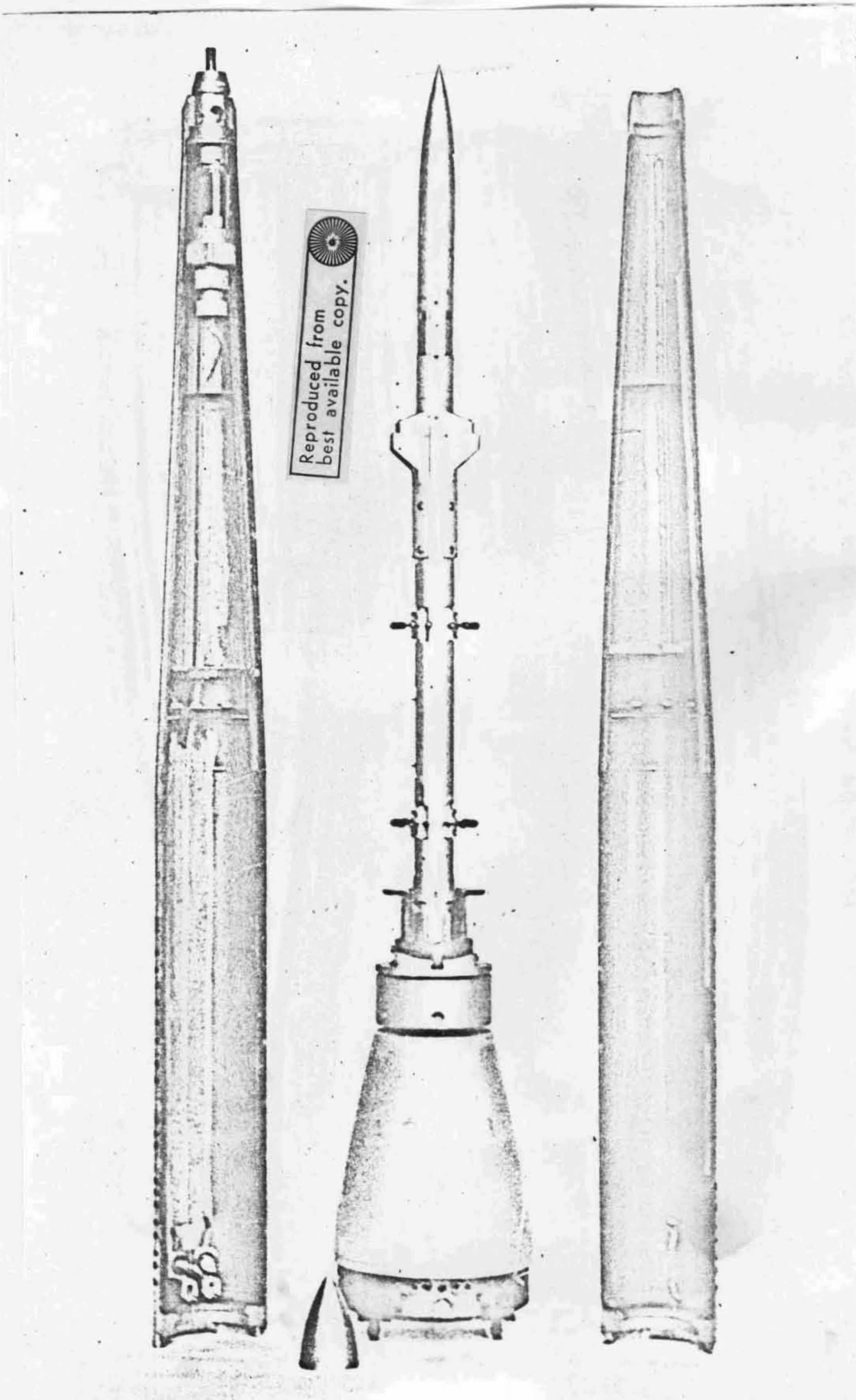


Figure 3c.

The spire is a round, tapered rod, the forward part of which contains the Pirani gauge. The struts for the main resistance thermometers are somewhat lower down on the spire. The struts are located along the spire, under the protective panels, when not in use. The struts extend into their working position, perpendicular to the axis of the spire, when the protective panels are jettisoned.

A special electrical plug provides the electrical connection between the instruments in the spire and the equipment in the instrument compartment.

The gauge unit consists of two Pirani gauges, one for the pressure range from 5 to 0.5 mm Hg, the other for the range from 0.5 to $5 \cdot 10^{-3}$ mm Hg. Each gauge consists of two measuring elements, and two compensating elements, the bulbs of which are made of glass. The dimensions of the bulbs of the measuring /6
and compensating elements are the same; length 100 mm; outside diameter 4.3 - 4.5 mm; inside diameter 2.5 - 3 mm. A fitting, connecting the gauge to atmosphere, is located 10 mm from the end of the bulbs. Tungsten wire is used as the thermometric material in the gauges. The first type uses a tungsten filament 13 microns in diameter, the second a tungsten coil with a diameter of 60 microns, wound of 10 micron diameter wire. The internal pressure in the bulbs of the compensating elements is selected such that it is a reference point for use in making the final check of the equipment. The bulbs therefore are sealed at a pressure of 750-760 mm Hg. A control resistance thermometer, made of enameled copper wire with a diameter of 30-34 microns, is used to measure the temperature of the heat gauge walls. The wire is wound on one of the bulbs of the heat gauges, which are installed in a separate unit connected to the forward part of the spire (Figure 4). The connections for the bulbs of one of the gauges extend from diametrically opposite sides of the spire for a distance of 6 calibers from its nose. The selection of the site for the exit of the connections is determined by the fact that the local pressure ratio is close to zero at a distance of 6 and more calibers from the nose, and does not depend on the shape of the nose. This design compensates for the influence of the angle of attack during small deviations from the axisymmetrical flow around the body.

The heat gauges are calibrated for pressure and temperature. The operative document used to process the measurement results is the single-parametric family of curves

$$V = f_{P_g}(T_g),$$

where

V is the voltage across the output of the gauge electric circuit;

T_g is the temperature of the gauge walls;

P_g is the pressure inside the gauge measuring volume. /7

A diaphragm pickup is used to measure pressure from 250 to 5 mm Hg. The measure of the pressure is the change in the resistance of a potentiometer, the slide of which is connected to the diaphragm of the aneroid capsule. Mounted on the pickup is the control resistance thermometer, the temperature reading of which is used during the processing of pressure measurements. Since the measurements made by the diaphragm gauge take place only during parachuting of the head, that is, when speed of movement is low, it can be taken that undisturbed atmospheric pressure is being measured.

The main resistance thermometers are mounted on contact crowns located on two round struts, with two thermometers on each strut. The sensor is a tungsten-rhenium alloy wire with an antiradiation coating of a gold and palladium alloy, or an uncoated tungsten-rhenium wire. Wire diameter is 35-39 microns, length 13 cm. Four thermometers increases the dependability of the measurements and increases the sensitivity of the method. The long length of the thermometric wires lessens the role of heat exchange between them and the contact crowns, and this too increases the accuracy of temperature measurements. The antiradiation coatings are necessary to reduce radiation heat exchange in the rarified atmosphere. Special experimental investigations have shown that in the case of a transverse flow around the filament of a thermometer, its reading will be less dependent on the angle of attack then when the flow is longitudinal.

Two thermometers are designed to measure the temperature from -100 to +250°C, and the other two from -20 to +350°C.

All pickups are connected in unbalanced Wheatstone bridge circuits with a common supply source. The voltage across each of the bridge diagonals changes from -100 to +100 mV. The entire range of parameters measured can be broken down into two subranges for the majority of the main pickups. The output signal in each subrange changes within the limits indicated above (Table 1). /8

The main thermometers and gauges are recalibrated on special thermometric and vacuum stands, with which all rocket sounding stations are equipped, but no earlier than 7 days prior to launch. The purpose of this check is to refine the

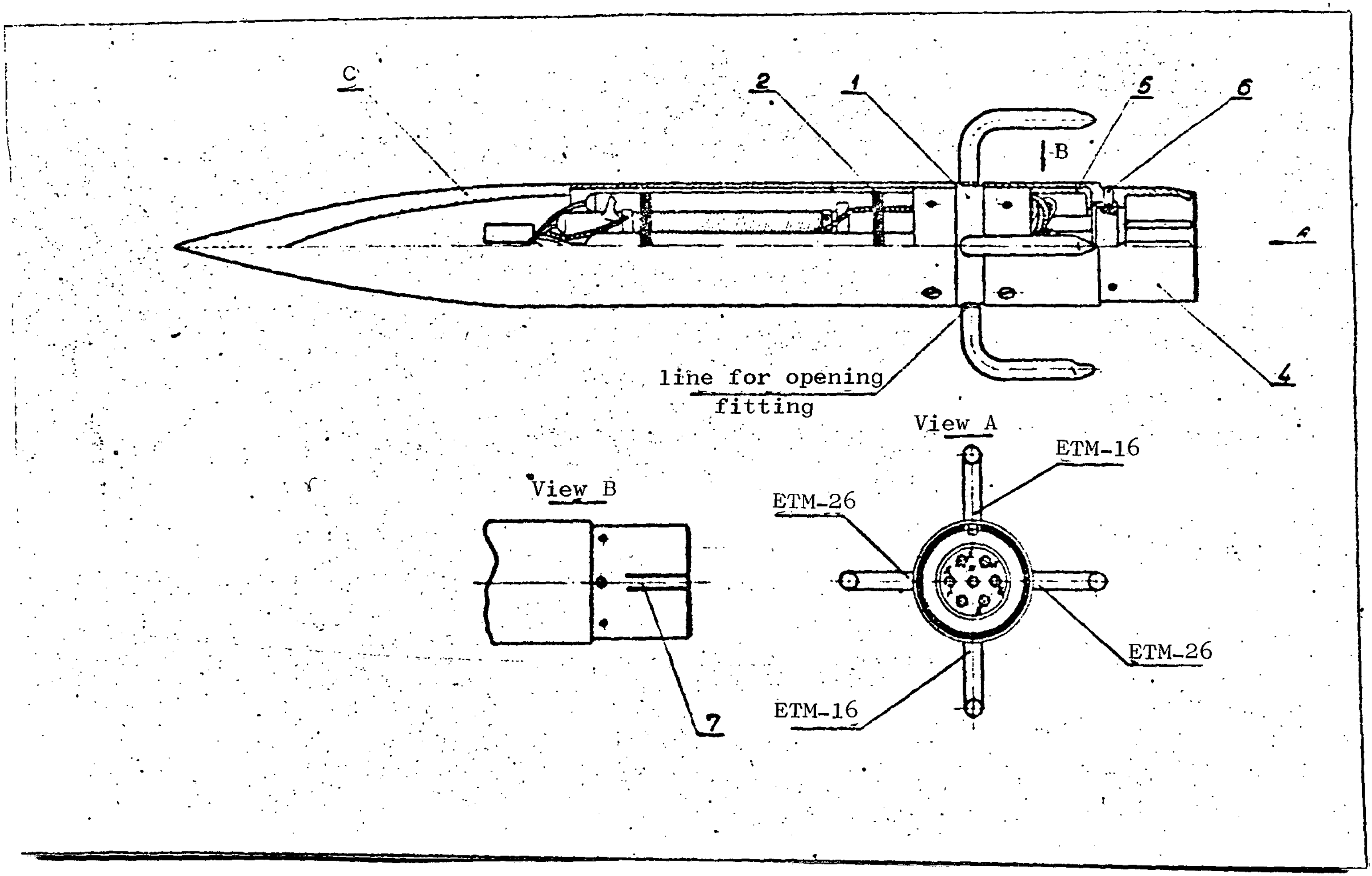

C
2
1
5
6
B
A
4
line for opening
fitting
View A
ETM-16
ETM-26
ETM-26
ETM-16
View B
7

Figure 4.

original calibration curves, which can change while the head is in storage.

The method used to calibrate the thermometers involves creating two temperatures inside a special temperature-controlled cabinet, and then measuring them precisely (the first temperature usually is close to ambient, the second is of the order of +80°C). The resistances of the thermometer wires are measured very precisely (within 0.05 percent) at these temperatures. The temperature inside the cabinet, T_c, is measured by a standard platinum thermometer accurate to within 0.05°C. The resistances for the two temperatures are then used to calculate the temperature coefficient of resistance, α, for each of the thermometers, as well as their resistance at 0°C, R_0. The second temperature coefficient of resistance, β, is known (the manufacturer of the wire provides it), so the relationship $R = f_1(T_c)$ can be obtained. The electric bridge circuit is calibrated by inserting standard resistances in place of the thermometers. Combining $V = f_2(R)$, where V is the bridge output voltage, with $R = f_1(T_1)$, we obtain $V = f(T_c)$, which can be used to decode the data obtained in flight. /9

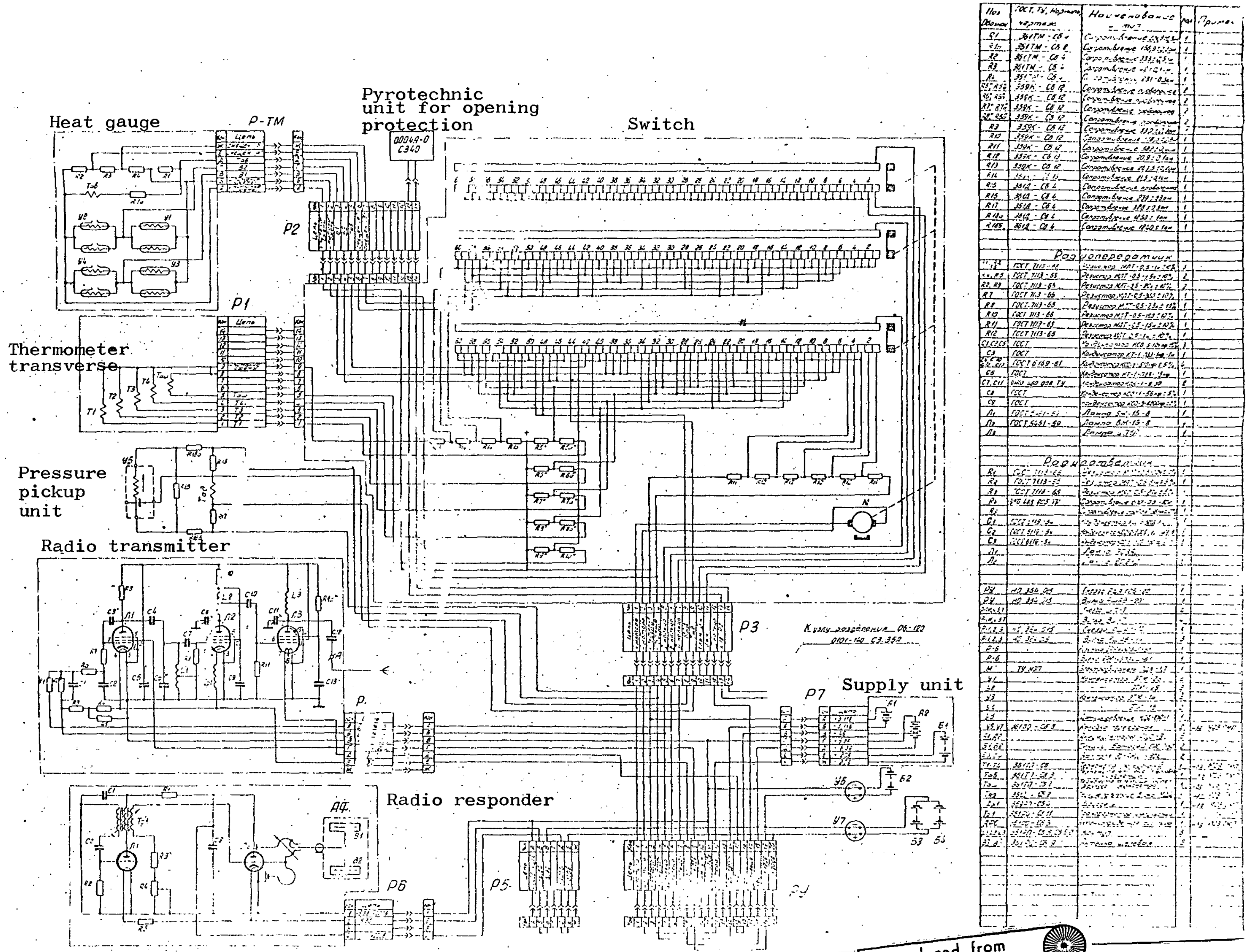
The heat gauges are calibrated in vacuum systems that use the standard McLeod gauge as the primary standard, and a standard thermocouple as the secondary.

TABLE 1.

No.	Instrument	Subrange	Parameter measurement limits From	To
1	First heat gauge	1	5	1.5 mm Hg
		2	1.5	0.5 mm Hg
2	Second heat gauge	1	0.5	0.05 mm Hg
		2	0.05	0.005 mm Hg
3	Diaphragm gauge	1	250	140 mm Hg
		2	140	5 mm Hg
4	First resistance thermometer	1	-20	200°C
		2	90	350°C
5	Second resistance thermometer	1	-100	100°C
			0	250°C
6	Third resistance thermometer	1	-20	200°C
		2	90	350°C
7	Fourth resistance thermometer	1	-100	100°C
		2	0	250°C
8	Control resistance thermometer for heat gauges	1	0	300°C
9	Control resistance thermometer for diaphragm gauge	1	-50	300°C
10	Control resistance thermometer for meteorological spire	1	-50	100°C

Figure 5 is the head's measuring diagram. The diagonals of the bridge circuits for the individual pickups are connected to the fixed contacts of a mechanical switch. The sliding contacts provide the alternate connection of the pickups to the input to the transmitter in the radiotelemetry line. /10

The switch has three contact rings, each of which has 60 contact points. The first two rings connect the diagonals of the pickup bridges, the third ring is the control ring. Connected to it is a network of resistors in the potentiometer circuit. Connection of each successive resistor with the common network occurs at the moment of passage from one contact point to another. A contact counter, an indicator that measures the voltage drop across the network is connected to the third ring. This instrument is calibrated for the number of contacts, so the switch can be set to the necessary contact point during the prelaunch head checks. The time to interrogate all 60 points on the switch



Heat gauge
P-TM
Pyrotechnic unit for opening protection
Switch
P2
P1
Thermometer transverse
Pressure pickup unit
Radio transmitter
P3
Supply unit
P7
Radio responder
P6
P5

Figure 5.

(the switching cycle) is 5 seconds. A small electric motor and reduction gearing rotate the switch. The permanent resistors in the bridge circuits, made of manganin wire, are mounted on the sides of the switch.

The radiotelemetry system operates on the principle of frequency-shift keying of a high-frequency signal. The output voltages from the pickups are connected to the transmitter in turn through the switch. The transmitter input circuit contains a reactance tube that converts change in voltage into a change in generator frequency. Frequency doubling occurs, and oscillation power is amplified. A half-wave dipole, shielded in the central strap of the parachute system, is used as the on-board antenna.

A radio receiver with a panoramic adapter and a photorecorder is used as /11 the ground receiver-recorder installation. The signal from the transmitter is supplied to the panoramic adapter from the first converter in the receiver. Here the width of the passband corresponds to the band of frequency deviation for the transmitter, so all signals from the transmitter, within the limits of the band of frequency deviation, are fed into the input to the second converter in the panoramic adapter. This same converter is supplied with voltage from the frequency modulated beat-frequency oscillator, the frequency of which changes automatically, and continuously, within the limits of the 100 kHz scanning band. The scope of the panoramic adapter is a cathode ray tube, the sweep of which is synchronized with the changing oscillator's frequency. The screen of the tube shows, in turn, the signals of all frequencies supplied by the rocket when the switch functions. Locations of signals on the sweep line determine the frequency of the received signal. The signals on the screen are photographed on motion picture film which is moved continuously by a film transport device in a direction perpendicular to the sweep line on the cathode ray tube. The flight time is printed on the film at 1 second intervals as it records the time counter. A calibration bridge, consisting of highly stable resistors, is used to calibrate the scale of the receiver in the radiotelemetry line during the flight of the rocket. The bridge has a row of diagonal outputs, so calibrated voltages, equal to 0, ±50, and ±100 mV, can be supplied to the radio transmitter input.

A change in oscillator frequency, within the limits of the passband, occurs three times during the time the moving contact is resting on a fixed contact in the switch, and three signals, corresponding to the condition of the pickup during the particular time interval, are photographed on the cathode ray tube. These three signals are readily distinguishable from noise, which is chaotic in nature, during decoding. This provides the radiotelemetry system with its /12 resistance to interference.

The principal technical characteristics of the radiotelemetry system are:

1.	number of channels	60
2.	time to interrogate all channels	5 sec
3.	root-mean-square error introduced into the radiotelemetry system as a result of the measurements	±1 percent
4.	carrier frequency, transmitter	22150 kHz
5.	carrier frequency deviation	±50 kHz when measuring a voltage of ±100 mV at the transmitter input
6.	input impedance, radio transmitter	20 kohms
7.	power, radio transmitter	at least 1.8 watts
8.	radio receiver sensitivity	2 microvolts

The power supply consists of dry cells and storage batteries with the following set of voltages: 3.11 volts for the electrical measuring circuit; 23 volts for the switch motor; 6.1 volts for the filaments of the tubes in the radar responder; 120-130 volts for the radio transmitter plate circuit; 230-250 volts for the radar responder plate circuit. The power supply is adequate for continuous operation of the on-board equipment for 1.5 hours.

The trajectory measurement system provides for determination of the present coordinates of the meteorological rocket during its flight. This is necessary in order to tie the measured parameters of the atmosphere to the altitude, and to calculate the components of the rocket's speed.

The equipment for trajectory measurements is a system with active and pulse radiation. The responder, which is installed in the head of the rocket, sends a response signal when interrogated by a pulse from the ground station. The slant /13 range can be determined from the delay in the response signal relative to the interrogation pulse. The equisignal zone method is used to determine the angular coordinates. The radar responder is built on a superregenerative circuit. It radiates continuously, and has two stages; a superhigh frequency oscillator, and a modulator. The superhigh frequency oscillator radiates a signal at the frequency of the ground radar, 1770-1795 MHz, perceives the interrogation pulses, and changing the nature of the radiated oscillations, forms the response signals. The response signal is some excess of pulse against the background of continuous radiation from the responder. This excess is followed by a pause, a brief disappearance of the signal. The modulator generates auxiliary oscillations, sinusoidal in shape, at a frequency of 800 kHz, necessary for the operation of the superhigh frequency oscillator in the superregenerative mode. When the superhigh frequency oscillator is modulated it radiates intermittently with a repetition frequency of 800 kHz.

The on-board antenna-feeder system consists of two slot-type antenna heads, coaxial feeders, and a distribution T. The antenna heads are secured to the envelope of the rocket head. The ground installation is a "Meteor" meteorological radar modified somewhat to track the meteorological rocket. The radar has the following main tactical and technical characteristics:

1.	frequency band	1770-1795 MHz	/14
2.	repetition rate, main pulses	833 pps	
3.	pulse power, transmitter	2200 kw	
4.	pulse duration, transmitter	0.8 μsec	
5.	sensitivity of receiver system	$6.5 \cdot 10^{-13}$ watt	
6.	diameter of paraboloid	1.83 meters	
7.	width of half power pattern	$6.5 \pm 1°$	
8.	range of automatic tracking of radiosonde	150 km	
9.	limits of operation in azimuth unlimited, in elevation	from 0 to 90°	
10.	root-mean-square errors in determination of angular data in automatic tracking mode	7.2'	
11.	root-mean-square errors in determination of range of radiosonde in automatic tracking mode	40 meters maximum	
12.	frequency of conical lobing of beam pattern	24 Hz	
13.	radar operating modes:		

(a) active tracking of meteorological rocket

(b) active tracking of radiosonde

(c) passive target tracking

14. rate of recording of spherical coordinates — 0.25, 1, and 5 seconds in "rocket" mode; 30 seconds in "radiosonde" mode
15. power requirement — 13.5 kw
16. recording method
    (a) in "rocket" mode - photography on motion picture film at range, elevation, and azimuth scales;
    (b) in "radiosonde" mode - printout on paper tape.

Operation in the "rocket" mode occurs during the first ten minutes after launch only, after which the operator switches the set to the "radiosonde" mode. /15

It is customary to make the radiotelemetric measurements with two receivers spaced some distance apart, and the target coordinate measurements with one radar. All recording points are interconnected and also are connected to the rocket launch control station, by telephone communication, as well as by a unified time line activated by a special chronometer. The unified time line is energized when the launch button is pressed, and sometimes from the launcher's heel contact.

Processing the Measurements

Measurements are processed in two stages. The first stage involves decoding the radiotelemetry and converting the magnitudes of the deviation of the signal from the zero line into numerical values corresponding to the magnitudes measured by the instruments. The second stage is the calculation of the free atmosphere parameters from instrument data.

A decoder, an instrument that can project signals from the telemetry film at a larger scale onto a special decoder screen, is used to decode the signals. Voltage values obtained from pickup operation are read off the film at numerical scales on a movable plotter fastened to the decoder screen.

Calibration curves are used to convert the voltage readings taken off the film in millivolts, into temperature (for the thermometers) and into pressure (millimeters [blank]) (for the pressure pickups). Calibrations obtained for the station several days prior to the launch are used.

The decoded telemetric information is presented in the form of curves, plotted in terms of time and time of launch, for convenience in future processing of sounding data. /16

The position of the rocket in space is fixed by the slant range, D, the angle of elevation, γ, and the azimuth, ω, measured by the radar.

The D, γ, and ω values up to 600 seconds are taken off the photographic film, and off the paper tape after 600 seconds, and are entered in a special table at time intervals of 5 seconds up to 600 seconds, and at 30 second intervals after 600 seconds.

The thermometer filament temperature, T_f, and the spire temperature, T_s, taken off the curves, the logarithm of the pressure, obtained from the heat and diaphragm gauges, and the heat gauge temperatures, T_g, are entered in this same table.

All subsequent data processing is by computer. Appendix I lists the procedure used to obtain final temperature, pressure, and wind data. The algorithm for computer processing is given in what follows.

The magnitudes D, γ, ω, T_f, T_s, log P_g, and T_g are computer averaged in order to reduce the effect of random errors. A sliding five-point averaging function is used for the purpose

$$\bar{f}(t_j) = \sum_{i=j}^{j+4} \frac{f(t_i)}{5} \tag{1}$$

where $j = 1, 2, \ldots n-4$

n is the number of values assigned to the function f(t);

f(t) is the notation for the functions D(t), $\gamma(t)$, $\omega(t)$, $T_f(t)$, $T_s(t)$, log $P_g(t)$, and $T_g(t)$.

The averaged angle and range values are used to calculate the rocket's coordinates and speed, as well as wind speed, using the relationships

$$x = D \cos\gamma \cos\omega \tag{2}$$ /17

$$y = D \cos\gamma \sin\omega \tag{3}$$

$$z = D \sin\gamma \tag{4}$$

$$h = \sqrt{x^2+y^2+(z+R)^2} - R + \Delta h \tag{5}$$

where

x is the meridional axis ("plus" to the north);

y is the zonal axis ("plus" to the east);

z is the vertical component;

h is the altitude above the surface (calculated with the earth's curvature taken into consideration);

R is the earth's mean radius;

Δh is the altitude of the sounding station above sea level.

The cumulative speeds at which the rocket moves in space are found by differentiating the approximating second-order parabola using the five-point least squares method; that is

$$F(t_j) = \frac{-2\varphi(t_{j-2}) - \varphi(t_{j-1}) + \varphi(t_{j+1}) + 2\varphi(t_{j+2})}{10\,\Delta t} \tag{6}$$

where

$j = 3, 4 \ldots n-6$;

$F(t)$ $\begin{cases} V_x(t) \text{ is the meridional component of the speed;} \\ V_y(t) \text{ is the zonal component of the speed;} \\ V_z(t) \text{ is the vertical component of the speed;} \end{cases}$

$\varphi(t)$ $\begin{cases} x(t) \text{ is the meridian coordinate;} \\ y(t) \text{ is the latitude coordinate;} \\ z(t) \text{ is the altitude of the rocket above the earth's surface;} \end{cases}$

Δt is the time interval for which the value of the function $\varphi(t)$ is given.

The speed of this movement must be taken into consideration in order to calculate the effect movement of the atmosphere has on pickup readings. Standard observations do not yet establish wind speed above 60-65 km, so the program for formulating rocket speed is calculated using two formulas. /18

The following relationship is used when the condition $|a_z - g| \geq 0.5$ is satisfied

$$V = \sqrt{V_z^2 + \Delta_x^2 + \Delta_y^2}$$

If this condition is not satisfied, then

$$V = \sqrt{V_x^2 + V_y^2 + V_z^2} \tag{9}$$

is used. Here

$$\Delta_x = |V_z| \frac{a_x}{a_z + g} \quad \text{and} \quad \Delta_y = |V_z| \frac{a_y}{a_z + g} \tag{8}$$

are the differences in the wind speed and rocket speed components, a_x, a_y, and a_z are the acceleration components for the rocket, calculated using Eq. (6), where the function $\varphi(t)$ is understood to mean the function $V_x(t)$, $V_y(t)$, $V_z(t)$, and g is the acceleration of gravity.

The wind speed components are calculated by using the formulas

$$V_x' = V_x + \Delta_x ; \qquad V_y' = V_y + \Delta_y \tag{10}$$

Filament temperature is corrected for all levels above 15-18 km by using the formula

$$T_f' = T_f + \Delta T_s = T_f + 0.06(T_f - T_s) \tag{11}$$

where the correction factor ΔT_s takes into consideration the influence of the thermal contact of the filament of the thermometers with the insulating rollers. The values of t, V, V_x', V_y', T_f', log P_g, and T_g must be tied to standard altitudes in subsequent temperature and pressure calculations as well as for practical use. Time t is tied to standard altitudes by linear interpolation. The tie for the values of the V, V_x', V_y', T_f', log P_g, and T_g functions is made using an approximating third-order parabola and the least squares method over an interval containing at least five points; that is

$$f(t) = C_0 + C_1 t + C_2 t^2 + C_3 t^3 \tag{12}$$ /19

where

C_0, C_1, C_2, and C_3 are coefficients that are the solutions of a system of fourth-order linear algebraic equations;

f(t) denotes the functions V, V_x', V_y', T_f', log P_g, T_g.

Substituting the times corresponding to the standard altitudes in Eq. (12), we obtain the values of the function f(t) at standard levels.

Wind speed, V', and its direction, $\beta°$, are found at all standard altitudes in terms of the wind components V_x' and V_y'

$$V' = \sqrt{(V_x')^2 + (V_y')^2}$$
$$\beta° = \operatorname{arctg}\left(\frac{V_y'}{V_x'}\right) \tag{13}$$

And

$$\beta° = \begin{cases} \Delta\beta° & \text{when } -V_x'; -V_y' \\ \Delta\beta° + \pi & \text{when } V_x'; \pm V_y' \\ \Delta\beta° + 2\pi & \text{when } -V_x'; +V_y' \end{cases} \tag{14}$$

Temperature is calculated using the formula

$$T_\infty = T_J' - 4.98 \cdot 10^{-4} r V^2 + \tau \frac{dT_J'}{dt} + \varepsilon\sigma \frac{(T_J')^4}{h} + \frac{Q_J}{5h} - \frac{\sum q_i}{h} \tag{15}$$

where

r is the temperature restoration factor, determined from the table,

$$r = f(M_\infty, \log Kn).$$

The Knudsen number is calculated using the formula

$$Kn = \frac{2.33 \cdot 10^{-5}\, T_\infty}{r_0\, p_\infty \left(1 + \frac{110.5}{T_\infty}\right)} \tag{16}$$

Here r_0 is the diameter of the thermometer filament, in cm, and P_∞ is atmospheric pressure in mm Hg.

The Mach number if found from the relationship

(17)

where

C is the speed of sound, and depends on the temperature

$$c = 20.057 \sqrt{T_\infty} \tag{18}$$

τ is the time constant for the heat thermometer, and is found by using the formula

$$\tau = \frac{c_0 \rho_0 r_0}{4h} \tag{19}$$

where

c_0 is the specific heat;

ρ_0 is the density;

$2r_0$ is thermometer diameter.

For standard thermometers in use today

$$\tau = \frac{7.2 \cdot 10^{-4}}{h} \tag{20}$$

The rate of change in the temperature of the thermometer filament during the flight of the rocket, $\frac{dT_f'}{dt}$, can be calculated by using the formula

$$\frac{dT_{fj}'}{dt} = 0.5 \left[\frac{T_{fj}' - T_{fj-1}'}{t_j - t_{j-1}} + \frac{T_{fj+1}' - T_{fj}}{t_{j+1} - t_j} \right] \tag{21}$$

The heat exchange factor for the thermometer, h, can be found from the relationship

$$h = \frac{0.1241 \cdot 10^{-2} \cdot T_\infty \sqrt{T_\infty}\, Nu}{T_\infty + 110.5} \tag{22}$$

The Nusselt number, Nu, depends on the Knudsen and Mach numbers. It can be /21
found by interpolating the values listed in the table

$$Nu = f(M_\infty, \log Kn).$$

The magnitude $\mathcal{E}\sigma(T_f)^4/h$ is considered to be the best radiation from the filament. Here $\mathcal{E}$ is the emission coefficient, depending on filament temperature, and σ is the Stefan-Boltzmann constant. The magnitude $\mathcal{E}\sigma(T_f')^4$ is found in the table listing the values of $\mathcal{E}\sigma(T_f')^4 = f(T_f')$. The heating of the thermometer by the current is taken into consideration by the term Q_J/Sh, where Q_J is the Joule heat emitted by the resistance thermometer, S is the thermometer's surface area.

$$Q_J = \frac{0.239\, U^2 R_0 (1 + \alpha t_f')}{[R + R_0(1 + \alpha t_f')]^2}, \tag{23}$$

where

R_0 is the resistance of the thermometer at 0°C;

U is the voltage of the battery supplying the thermometer bridge (U = 3.11 to 3.12 volts);

$t_f' = T_f' - 273$;

R is the resistance of the thermometer bridge arm.

The correction factor $\sum_i q_i/h$, which takes into consideration the radiant heat flux to the thermometer, long wave, and particularly shortwave, can be determined by using the formula

$$\sum_i q_i = \varepsilon\sigma (T_f')^4 - Q_J + h(T_f' - T_e) \tag{23^1}$$

$$T_e = T_\infty (1 + 0.2\, r\, M_\infty^2) \tag{24}$$

where all magnitudes are calculated for the trajectory peak.

Determination of a number of the parameters needed to calculate the temperature of the atmosphere from resistance thermometer readings requires a knowledge of temperature and pressure distribution in the atmosphere. Used for /22 this purpose as a first approximation are the values of temperature and pressure from the Soviet Standard Atmosphere 1964.

The pressure found by using the barometric formula, and the temperature values from the preceding approximation, is used in the next approximation when calculating temperature.

$$P_\infty(z_j) = P_{0\infty} \exp\left\{-0.28674 \sum_{i=1}^{j-1} \left[\frac{T_{\infty i}}{9.806 + 3.08 \cdot 10^{-6} z_i} + \frac{T_{\infty i+1}}{9.806 + 3.08 \cdot 10^{-6} z_{i+1}}\right]\right\} \tag{25}$$

where

$P_{0\infty}$ is the pressure at some lower level, determined from radiosonde data.

The iteration process continues until the difference between succeeding approximations is less than 0.01 percent.

The density of the atmosphere is calculated from temperature and pressure values found in the last approximation

$$\rho_\infty = 464 \frac{P_\infty}{T_\infty} \left(\frac{g}{m^3}\right) \tag{26}$$

where

P_∞ is in mm Hg;

T_∞ is in °K.

A correction factor for the thermal inertia of the gauge, τ_g, is introduced when processing the Pirani gauge readings. The time lag for this purpose is determined from gauge readings and the table of $\tau_g = f(\log P_g)$. The inertia correction factor for altitude is calculated in terms of the time lag, τ_g

$$\Delta H = \tau_g V_z \tag{27}$$

where

V_z is the vertical speed.

The pressure measured by the gauges will be equated to the altitude by

$$H' = H - \Delta H \tag{28}$$

The calculation of the pressure P_∞, is made using the formula

$$P_\infty = P_g \frac{\left[\frac{T_\infty}{T_g}\left(1 + 0.17 M_\infty^2\right)\right]^\nu}{1 + 0.7 \bar{p} M_\infty^2} \tag{29}$$ /23

where

ν is the thermal effusion factor, found by using the formula

$$\nu = \frac{3.822 \left(\frac{l}{a}\right)^2}{1 + 4.888 \frac{l}{a} + 7.644 \left(\frac{l}{a}\right)^2} \tag{30}$$

Here a is wire diameter, l is the length of the free path

$$\ell = 1.589 \frac{\mu \sqrt{T_g}}{P_g} \tag{31}$$

The coefficient of viscosity, μ equals

$$\mu = \frac{1.4832 \cdot 10^{-5} \cdot T_g^{3/2}}{T_g + 110.6} \tag{32}$$

where

T_g is the gauge wall temperature;

P_g is the pressure measured by the gauge.

The pressure ratio for the pressure adapter, $\bar{P}$, is found from the $\bar{P} = f(M_\infty)$ table. The magnitude ν is found from this pressure and the iteration process continues until the difference between successive approximations is less than 0.01 percent.

The P_∞ values obtained in the last approximation are interpolated linearly to standard altitudes.

The computer program envisages the readout of the results in the form of tables and curves, as well as the recording of the results on magnetic tape. An example of such a recording for one launch is contained in Appendix No. 2.

The sounding data, after analysis, are edited and computerized in the form of a standard bulletin.

An example of the final print out is listed in Appendix No. 3.

The maximum relative error in determining the pressure is 10 percent at an altitude of 50 km, and 30 percent at an altitude of 80 km. The maximum absolute /24
error in determining the temperature is 5° to 8° at 50 km, and 15° to 20° at 80 km. The root-mean-square error in determination of wind from parachute drift at an altitude of 40 - 50 km is 12 m/sec in speed and 10° in direction.

The meteorological rocket complex described is used to measure the parameters of the high layers of the atmosphere from ground sounding stations, as well as from research ships. The data provided by the complex are used for physicometeorological investigations.

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